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S/N 09/844477

PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant:	MALANEY et al.	Examiner:	Unknown
Serial No.:	09/844477	Group Art Unit:	2681
Filed:	04/27/2001	Docket No.:	3961.46US01
Title:	TELECOMMUNICATIONS TRAFFIC REGULATOR		

CERTIFICATE UNDER 37 CFR 1.10
'Express Mail' mailing label number: EL913562772US
Date of Deposit: 28 August 2001
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By: Omesh Singh
Name: Omesh Singh

SUBMISSION OF PRIORITY DOCUMENT

Assistant Commissioner for Patents
Washington, D.C. 20231

Dear Sir:

The Applicants enclose herewith one certified copy of an Australian application, Serial No. PQ 7125, filed 27 April 2000, the right of priority of which is claimed under 35 U.S.C. § 119.

Respectfully submitted,

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I, CASSANDRA RICHARDS, TEAM LEADER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. PQ 7125 for a patent by COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION filed on 27 April 2000.

WITNESS my hand this
Eleventh day of May 2001

CASSANDRA RICHARDS
TEAM LEADER EXAMINATION
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S&F Ref: 485662

ORIGINAL

AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION FOR THE INVENTION ENTITLED:

Telecommunications Traffic Regulator

Name and Address of Applicant:

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This invention is best described in the following statement:

TELECOMMUNICATIONS TRAFFIC REGULATOR

Technical Field of the Invention

The present invention relates generally to the field of telecommunications traffic management, particularly in the context of packet networks. The invention relates to a method and apparatus for regulation of packet traffic. The invention also relates to a computer program product including a computer readable medium, having recorded thereon a computer program for regulating packet traffic.

Background Art

High speed digital networks which integrate different sources of traffic are rapidly becoming the foundation of telecommunications. A fundamental requirement of a telecommunications network is the capability to provide a user of the network with predictable performance levels. In the public switched telephone network (PSTN), network dimensioning to achieve a specified Quality of Service (QoS) is a mature discipline.

The art of PSTN traffic forecasting is also well developed, the combination of forecasting and network dimensioning providing PSTN users with predictable performance at an acceptable cost to the network provider as the network grows to meet user demand. Provision of predictable QoS in modern high speed packet networks however is imprecise, and still largely a research topic. This is largely because such integrated digital networks carry stochastic traffic whose characterising attributes are not as well understood as those of PSTN traffic.

A number of terms are used throughout the description, and for clarity they are defined here. A packet is a unit of information carried by a network of fixed or variable

length. A "multiplexer" is a network element, with a number of inputs and a single output. A multiplexer typically includes an input packet buffer and typically uses a FIFO scheduler for allocating the connections from each input to the output on a packet by packet basis. There are a variety of scheduling algorithms used to allocate capacity between the users. In the general case, multiplexers can also have more than one output. A "switch" is a network element with a number of incoming links, its function being to switch traffic of each session to the correct outgoing link. A switch can in general contain one or more multiplexers. There are a variety of network elements which are used to modify the characteristics of traffic passing through a network.

A shaper is a device with an input and an output, which contains a buffer and varies the delay of packets passing through it so that its outputs are constrained to meet certain specified criteria, such as peak packet rate, sustained packet rate and/or average packet rate. A policer is a device with an input and an output which will discard packets which would make its output traffic exceed a specified rate over a specified time. Alternatively instead of discarding these packets the policer may mark these packets as non-conforming to be discarded by other network devices if required. By the term "regulator" we shall mean a device with an input and output which can perform as either a "policer", or a "shaper", or both.

Considering general QoS issues, Fig. 1 shows a terminal 100 connected by a transmission path 102 to an edge switch 104 in a network 106. The terminal can, for example, be a boundary router in a business enterprise, the router being used to connect corporate users on a corporate Local Area Network (LAN) to a public network. The edge switch 104 is connected, as depicted by a dashed line 108 symbolising one or more tandem transmission paths, to a second edge switch 110. This edge switch 110 is connected by a transmission path 112 to a second network 114, and thereafter by a

transmission path 116 to a terminal 118. The terms "transmission path", "connection", and "line" are used interchangeably in the description.

The users of terminals 100 and 118 are interested in achieving a predictable QoS end-to-end, as depicted by an arrow 128. The end-to-end QoS is, however, composed of individual per-network QoSs 124 and 126. The per-network QoS 124 is, in turn, composed of a series of inter-switch QoSs 120, 122 ... and so on. Accordingly, the Figure shows how the end-to-end QoS 128, which is of interest to the users of end terminals 100 and 118, is composed of a plurality of tandem QoS paths which describe a connection between the terminals. The aforementioned description applies equally to circuit switched networks such as the PSTN, and to packet networks. Important QoS parameters include loss, end to end delay and end to end jitter caused by the delays and/or overflows in the finite buffers in the various network elements between the two users.

Fig. 2 shows the terminal 100 and the edge switch 104 in more detail for the case of a packet network. For simplicity, the terminal (eg the boundary router referred to in relation to Fig. 1) is assumed to contain only one multiplexer and one output. Each incoming traffic source 200-202 is regulated in a regulator 208, the sources thereafter being aggregated in a buffer/FIFO scheduler 209 which forms a front end of a multiplexer 204. The multiplexer 204 outputs a regulated traffic stream on the transmission path 102 which connects across the network boundary 106 to the edge switch 104.

A number of traffic sources 216-218 are similarly input to a terminal 214, which produces regulated traffic on a transmission path 220. The switch 104 can perform the switching function alone, or alternatively, can in addition perform similar regulation/aggregation functions as described in respect of each terminal 100 and 214. In this latter case, the switch outputs a regulated traffic stream on the connection 108. Accordingly, the figure shows how a plurality of traffic sources 200-202, 216-218 are

successively aggregated and regulated in a tandem series of regulating "devices" 100, 214 and thereafter, 104 ... and so on.

Fig. 3 shows a prior art regulator 208 acting as a shaper, used in traditional packet networks, in more detail. The shaper 208 has an input traffic stream on the transmission path 206, and produces a regulated output traffic stream on the transmission path 102. The regulator 208 can be a token bucket regulator (TBR).

In the token bucket regulator shown in the figure, there is a FIFO buffer 300 and a switch 302 for transmitting bits from the buffer to the output 102. The occupancy of the buffer 300 is denoted by 312. The switch 302 is controlled by a Token Bucket regulation process 313 (conceptually a token bucket 306) with inputs being token bucket size σ 310, and a token input rate ρ 308. The regulation process 313 has an output (embodied as a control line) 304. Tokens 308 are continually put into a bucket 306 of size σ at a certain specified rate ρ 308. Each token present in the bucket corresponds to permission for the regulator to send a number of bits k_B into the network 102. The bucket itself has a specified capacity 310. If the bucket fills to this capacity, newly arriving tokens are discarded. When transmitting a packet, the regulator must remove from the bucket a number of tokens corresponding to the packet size.

If there are not enough tokens in the bucket to send a packet, the packet either waits in the buffer 300 until the bucket has enough tokens or the packet is discarded if the buffer occupancy 312 is too high. Therefore the largest burst a source can send into the network is proportional to the size of the bucket. TBR operation dictates that either the packet buffer 300, or alternatively the token bucket 306, is empty.

A token bucket regulation process can be used to define a rate of transfer. It has two defining parameters, namely a burst size and a mean rate, where:

Mean rate; specifies how much data can be sent or forwarded per unit time on average;

Burst size; specifies in bits per burst how much can be sent within a given unit of time.

The output rate will in practice be limited by the output capacity of the interface 102. The regulation imposed by a token bucket regulator can be described as follows. The TBR imposes on the input traffic flow 206 a bound for all times t, s $(0 \leq s \leq t)$ such that the following mathematical inequality holds:

$$A(t) - A(s) \leq k_B\, \sigma + \rho(t - s)\, k_B \qquad (1)$$

where; $A(t)$ is the number of bits arriving on 102 in time interval [0,t].

It is noted that the term leaky bucket is also in common usage for a regulator which provides the above constraint.

A TBR provides traffic shaping as it permits burstiness but places a bound thereon. The TBR guarantees that the burstiness is bounded so that the flow will never exceed the token bucket's capacity plus the time interval, multiplied by the token input rate as shown in Equation (1). It also guarantees that the mean transmission rate will not exceed the token input rate.

If the input traffic at 206 is non-Markovian, then the output traffic will also be non-Markovian. Markovian input traffic can be modified and become non-Markovian. Systems with this characteristic can not in general be analysed quantitatively.

Peak-rate, and similar simplistic methods of traffic dimensioning, provide guaranteed QoS to the users of all the terminals, based on a regulated peak rate requirement of each terminal. However, since typical terminal input traffic, e.g. 200, has a high peak-to-average traffic rate, peak-based traffic dimensioning makes inefficient use of network resources, and hence is uneconomical and not favoured by network operators.

Markov theory and effective bandwidth theory would appear to provide a promising tool for economical network dimensioning on a basis other than peak-rate based dimensioning, for networks which carry stochastic packet traffic. The use of Markov modulated processes enables issues such as buffer overflow in network switches to be addressed, providing a basis for network dimensioning and traffic engineering in cases where the traffic streams can be modelled as Markov processes. A major problem is encountered, however, when attempting to apply effective bandwidth methods to real network traffic, since such network traffic is exceptionally difficult to model, and typically cannot be represented as Markov processes. Furthermore, real traffic appears to contain long range correlations and elements of self-similarity, such traffic is not able to be represented by Markov processes.

In order to illustrate the difficulties encountered, an emerging network technology, capable of transporting and switching multi-service traffic, is considered. Asynchronous Transfer Mode (ATM) is one of the emerging network technologies which can support mixed traffic types. ATM connections fall into several classes, three of which will be considered. The connection types to be discussed are Constant Bit Rate (CBR), Variable Bit Rate (VBR) and Unspecified Bit Rate (UBR). Network infrastructure is typically provided to police connections in such a manner that connections defined to be one of the aforementioned connection types, is maintained within a corresponding envelope of characteristics. In the following description, the term "source" is used to represent a source of traffic which is policed in order to ensure that the traffic stream conforms to the necessary connection type definition.

A CBR connection requires, in general, only a Peak Cell Rate (PCR) traffic descriptor, where the PCR is the amount of bandwidth allocated to the CBR connection. A CBR service is expected, by a customer requiring such a connection, to comply with

his stated PCR. A VBR connection, in contrast, requires at least three traffic descriptors, thereby distinguishing VBR traffic from CBR traffic. VBR connections require, in addition to the PCR, a Sustainable Cell Rate (SCR) definition, and an Intrinsic Burst Tolerance (IBT) parameter. It is to be expected that the additional overhead incurred in specifying the aforementioned additional parameters provides a benefit, and it does so, in terms of an ability to share network resources. This benefit is realised in terms of a resource utilisation gain, which is commonly referred to as a "Statistical Multiplexing Gain" (SMG). In broad terms, there is a benefit to be had by setting up m (m > n) VBR connections, rather than merely setting up n CBR connections. Considering n sources with the same statistical characteristics, the SMG is expressed mathematically as follows:

$$SMG = n\rho(1) - \rho(n) \qquad (2)$$

where $\rho(1)$ is the PCR of the traffic;

$\rho(n)$ is the sum of effective bandwidths (ie. ρ_e) of each traffic source.

The significance of the SMG can be understood by considering a typical network configuration (see "ATM Network Performance" by George Kesidis, Kluwer Press, 1996, Chapter 7 for more detail) having a traffic requirement of 150 connections. For a typical set of traffic descriptors, either 60 CBR connections, or alternately, 190 VBR connections, can be accommodated. This conforms to an SMG of 2×10^6 cells per second.

The aforementioned example requires both a knowledge of the statistics of the incoming traffic streams, and also a theory on how to calculate effective bandwidth, ie. ρ_e. Calculation of ρ_e requires that a specified bound be placed on the acceptable level of "jitter" which is added to source traffic as it traverses the network, and accordingly, ρ_e is a function associated with the traffic stream. To be of practical value, ρ_e < PCR, because if ρ_e = PCR, the situation reverts to the CBR case (in which case the specification is that

zero jitter be added to the traffic source). It is thus noted that VBR traffic approaches a CBR traffic characteristic in the limit, where ρ_e approaches the PCR of the policed traffic source.

A UBR connection, or, as it is termed in the telecommunications industry, a "best effort service", is similar to a VBR connection, in that it is statistical (ie not CBR) in nature. However, a UBR connection is not associated with any formal traffic descriptors or quality of services (QoS) requirements. UBR connections are typically provided when the network has excess bandwidth available, and UBR defined traffic is carried through the network with no performance guarantees.

Addressing the concept of effective bandwidth in more detail, it is instructive to consider the sequence $x_1, x_2 \ldots, x_n$ being a sequence of n random variables. The aggregate of these variables S_n can be expressed mathematically as follows:

$$S_n = \sum_{k=1}^{n} x_k \tag{3}$$

where S_n is a summation of the random variables, and x_k...are said random variables.

The theory of large deviations can be used to calculate the probability of log $P[S_n > ny]$

where: log is the natural logarithm function

P() denotes a probability, and

y is some variable.

The desired probability, in the limit as n approaches infinity is provided by the following mathematical representation:

$$\log P\,[S_n > ny] = -nI(y) \tag{4}$$

Where: $I(y)$ is the rate function of the input process.

The logarithm of the moment generating function $\Lambda(\theta)$ of the random variable $x = x_1$, is now introduced, this being expressed mathematically as follows:

$$\Lambda(\theta) = \log E(\exp(\theta x)) \qquad (5)$$

where: E() is the expected value function

exp() is the exponential function

In the more general case where the variables $x_1, x_2, \ldots x_n$ are not independently and identically distributed (i.i.d.) then equation (5) is replaced by the following:

$$\Lambda(\theta) = \lim_{n \to \infty} \frac{1}{n} \log E(\exp(\theta \sum_k x_k)) \qquad (6)$$

This is referred to as the asymptotic log moment generating function (ALMGF).

With these definitions the function $I(y)$ can be written as follows:

$$I(y) = \sup_{\theta}(\theta y - \Lambda(\theta)) = \Lambda(y)^* \qquad (7)$$

where: Λ^* is the Fenchel (ie. Legendre) transform of Λ, and

sup is the supremum of this function. See A. Dembo, O. Zeitouni, "Large Deviation Techniques and Applications", Jones and Bartlett, 1992 for further details.

The negative of the rate function $I(y)$, ie. $-I(y)$ is commonly referred to an the entropy function of the input process. Assuming the existence of a well defined entropy function $-I(y)$ for a given input sequence $x_1x_2\ldots, x_n$, the equivalent bandwidth ρ_e of that sequence can be expressed mathematically as follows:

$$\rho_e(\theta) = \Lambda(\theta)/\theta \qquad (8)$$

It is noted that $\rho_e \geq \rho_m$, where ρ_m is the mean rate of the source.

The effective bandwidth is an important concept as will be shown later in the description. Given j sources each with effective bandwidths ρ_e^{j}, if this aggregation of j sources enters a buffer size B with output rate ρ then

$$\sum_j \rho_e^j \leq \rho \Rightarrow \lim_{B\to\infty} \frac{1}{B} \ln P\{X > B\} \leq -\theta \qquad (9)$$

where X is the buffer occupancy.

Effective bandwidth, ie. ρ_e, is often associated with the problem of inputting a traffic stream into a buffer which has a single output rate ρ. ρ_e can be specified to be a value which guarantees, in the limit of large buffer occupancy, that the slope of the log P versus buffer occupancy is a straight line with slope θ_o. The value of ρ which meets this condition can be expressed mathematically as follows:

$$\rho_e\theta_o - \Lambda(\theta_o) = 0 \qquad (10)$$

This mathematical formulation can be applied to the previous statistical multiplexing example as follows. Assuming that a traffic source has a well defined ALMGF $\Lambda(\theta)$, then the parameter θ is set in a manner which places a tolerance on acceptable jitter. Equation (8) can be used to calculate, thereafter, the effective bandwidth ρ_e. The fact that this ρ_e is less than the PCR of the traffic being considered illustrates the fact that statistical multiplexing gain has been achieved.

The mathematical formulation can be applied to a telecommunications network application, and in particular a Call Admission Control (ie. CAC) procedure on an ATM VBR link. A Network Management Administrator (NMA) has a node up and running with n input links, and a single output link with rate R. If the input links are being scheduled in the output link in such a manner that the requested QoS requirements for each input link are to be satisfied, this requires that the Network Management Administrator must allocate a required amount of his available network bandwidth to the current users.

When a new user appears and requests a specific QoS for his new traffic stream, the network management administrator must accomplish, in real time, a decision as to whether the resources are available to accommodate this request. It is noted that for the purposes of the following analysis, all existing and new traffic sources are assumed to possess well defined ALMGF $\Lambda(\theta)$. The network management administrator preferably uses the concept of effective bandwidth to make this decision. If the new user has traffic with a means rate $\rho = \rho_m$ and requests a QoS defined by a value α_o, the network management administrator must solve the following mathematical equation:

$$\rho_e = \Lambda(\alpha_o)/\alpha_o \qquad (11)$$

If unallocated network bandwidth greater than the aforementioned value of ρ_e is available, the new user is accepted for connection to the network. If, however, unallocated bandwidth is not available to this extent, the new connection is refused.

Fig. 4 depicts the previous mathematical discussion in graphical terms. The abscissa in this figure indicates how many users can be connected to the network, dependent upon an amount of bandwidth allocated to each user, (noting that there are three different types of allocation schemes depicted), as indicated by the ordinate. The figure shows a plot of bandwidth requirements 700 as a function of number of active calls (ie. sources) or users 702. The lower curve 708 shows a number of users which can be allocated if only the average bandwidth of the source is allocated. In this case, a large number or users 716 can be accommodated, however the QoS guaranteed to each user will be poor, the only parameter guarantee being available being a maximum delay specification for each packet. The centre curve 706 is a "middle ground", where, ideally, effective bandwidth theory is used to obtain benefit from a higher QoS specification, while still retaining advantage from statistical multiplexing. Finally, the upper curve 704 shows the number of users which can be allocated if peak bandwidth is assigned to each

user. In this case, no statistical multiplexing gain is available, however a high QoS is achieved (ie. essentially zero delay). This is achieved at the expense, however, of minimising the number of allowed users.

In practice, determination of the centre curve cannot presently be done in a quantitative fashion. Accordingly, network engineers must fall back on use of simulations, or experience of past traffic specifications to estimate the effective bandwidth, thereby "solving" the CAC problem posed above. Clearly, this is inaccurate at best, and real time CAC decisions can only be made using rules of thumb.

Disclosure of the Invention

It is an object of the present invention to substantially overcome, or at least ameliorate, one or more disadvantages of existing arrangements.

According to a first aspect of the invention, there is provided a method of regulating input packet traffic, said method comprising the steps of:

constraining said input packet traffic;

conforming said constrained input packet traffic in relation to a stochastic distribution function; and

producing output packet traffic having a well defined entropy bound.

According to another aspect of the invention, there is provided a traffic regulator, comprising:

constraint means, adapted to constrain input traffic; and

conforming means adapted to conform said constrained input traffic to a stochastic distribution function to produce output packet traffic characterized by a well defined entropy bound.

According to another aspect of the invention there is provided a computer program product including a computer readable medium having recorded thereon a computer program for implementing the method described above.

Brief Description of the Drawings

A number of preferred embodiments of the present invention will now be described with reference to the drawings, in which:

Fig. 1 shows Quality of Service (QoS) evolution within and across networks;

Fig. 2 shows aggregation and regulation of traffic;

Fig. 3 depicts a prior art token bucket regulator;

Fig. 4 depicts user volume/performance curves in a network;

Fig. 5 shows an entropy regulator in accordance with a preferred embodiment of the present invention;

Fig. 6 shows a flowchart of method steps for the regulator of Fig. 5;

Fig. 7 shows unregulated TCP/IP traffic;

Fig. 8 shows the traffic in Fig. 8 after regulation in accordance with the preferred embodiment; and

Fig. 9 is a schematic block diagram of a general purpose computer upon which the preferred embodiment of the present invention can be practiced;

Detailed Description including Best Mode

Where reference is made in any one or more of the accompanying drawings to steps and/or features, which have the same reference numerals, those steps and/or features have for the purposes of this description the same function(s) or operation(s), unless the contrary intention appears.

In the context of this specification, the word "comprising" means "including principally but not necessarily solely" or "having" or "including" and not "consisting only of". Variations of the word comprising, such as "comprise" and "comprises" have corresponding meanings.

In a preferred embodiment of the present invention, a new regulation device, ie an "Entropy Regulator" (ER), is disclosed, which imposes probabilistic, rather than deterministic, upper bounds on input traffic flows. In general, the ER can impose a well defined entropy bound on traffic, this having desirable properties described below. In particular however, a particular type of entropy bound, ie Exponentially Bounded Burstiness (EBB), is found to have particular advantages in relation to telecommunications networks operation and planning.

The ER for EBB (described as an EBB/ER in the description) is defined so that by careful selection of two parameters which control the statistical information imposed on the input traffic, EBB is imposed on the output traffic. This then allows effective bandwidth principles to be applied, enabling much more efficient use of network resources to be achieved.

That is, use of the EBB/ER allows end users to define their requirements in terms of a statistical probability of achieving a certain QoS, rather than specifying a deterministic bound. This approach in general proves to be more cost effective. From a purely illustrative perspective, it can be visualised that whereas in the TBR the token bucket remains fixed in size, in the EBB/ER the size of the token bucket becomes a random variable, with a probability distribution given by $W(x)$. During operation, at a chosen time-slot t, a uniform random variate x, is chosen which then sets the value of $W(x)$ for that time-slot.

As noted, use of EBB/ERs in networks impose EBB on traffic. .EBB traffic is more tractable in terms of traffic engineering and network dimensioning. For example, if all traffic entering the network is EBB, then aggregations of traffic within the network are also EBB. This allows probabilistic bounds of QoS parameters such as time delay to be calculated.

Solution of the Connection Admission Control problem requires availability of a well defined ALMGF $\Lambda(\theta)$ (see Equation (6)) for the various traffic sources being considered. This well defined moment generating function leads, in turn, to an assumption of a well defined entropy function $-I(y)$ as defined by Equation (7). Mathematically, a number of well known models of traffic sources, such as Poisson, Bernoulli, and Markov process, have well defined entropy. The problem is, however, that real traffic sources cannot, in general, be modelled by such mathematically convenient descriptions.

Real traffic sources are more complex, and can involve long range correlations. This divergence between real world traffic and the mathematical models typically used to model traffic, is at the core of the problems underlying the application of mathematical and engineering theory to real networks. For example, the Connection Admission Control procedure previously outlined does not actually work in practice (ie rule of thumb must be resorted to), because typically, real traffic sources have ill-defined entropy. Consequently, effective bandwidth theory cannot be applied, and therefore, accurate resource requirements and allocation cannot be determined.

It is shown, however, that real traffic sources can be regulated in such a manner that a bound is placed on the entropy of traffic output from the regulating device, ie the ER. By use of the ER, a firm upper bound to the effective bandwidth necessary to meet a required QoS specification can be calculated.

A preferred embodiment of the entropy regulator has, at its core, a process providing a constraint to which the regulated traffic flow must conform. This constraint can be expressed mathematically as follows:

$$\Pr\{O(t) - O(s) \leq (t - s)\rho + f(\alpha, x)\} \leq F(\alpha, \sigma) \qquad (12)$$

for all times $s(0 \leq s \leq t)$,

where: $O(t)$ is the number of bits seen on the regulated flow in the time interval $[0,t]$,

ρ is an as yet unspecified rate; and

F is a distribution function involving parameters α and σ.

A function f, being the inverse function of F, is used to realise the form of F from a uniform random variate $x(0 \leq x \leq 1)$. In general, any probability distribution function for F can be used.

For example, if F is defined by the following mathematical expression:

$$F(\alpha,\sigma) = 1 - e^{-\alpha\sigma} \qquad (13)$$

then the following corresponding inverse representation is derived:

$$f = F^{-1}(x) = (1/\alpha) \log [1-x]^{-1} \qquad (14)$$

Given Equation (14), the process producing traffic which satisfies the constraint of equation no. (12) will satisfy, for all times s, the following mathematical equation:

$$\Pr\{O(t) - O(s) \geq (t - s)\rho + \sigma\} \leq e^{-\alpha\sigma} \qquad (15)$$

Traffic which satisfied equation (15) is said to possess Exponential Bounded Burstiness (EBB). As noted, the preferred embodiment of the entropy regulator which utilises F as defined by Equation (13) provides an output traffic stream which has exponentially bounded burstiness. Another advantage of the described process is that there exists an analytical expression Equation (14) for the inverse of the distribution function defined in Equation (13).

Many types of traffic sources, including Markov Modulated processes, satisfy the EBB constraint equation. That is, one can find parameters, ρ and σ for the EBB Equation (15), such that this equation will produce a bound for any chosen Markov Modulated process.

Another unique feature of traffic which satisfies the constraint Equation (15) can be found from the consideration of what happens to the probability P of buffer occupancy in a downstream network node. For such traffic a straight line bound of the Log P vs. Buffer plane (see Fig. 8) is obtained for all buffer sizes - not just the large buffer limit obtained from Large Deviations Theory.

As previously noted, traffic which satisfies the EBB constraint equation is a special case of the more generalized constraint. The more generalized constraint is obtained by the use of any distribution function F in the constraint Equation (12), rather than the specific F in Equation (13), which leads to EBB traffic. The embodiment described below in relation to Figs. 5 and 6 can be readily altered to provide bounds on the traffic which are not EBB, but satisfy other, well formed entropy, constraints. This is achieved by replacing the function f (the inverse of the distribution function F in Equation (13), which is used to determine the "bucket size" at the control step 510 (see Fig. 6) by an alternative function.

This covers a much broader spectrum of traffic sources, including those possessing sub-exponentially bounded burstiness such as "self-similar fractional Brownian Motion". See D. Starobinski and M. Sidi, "Stochastically Bounded Burstiness for Communication Networks", IEEE Transactions on Information Theory Vol. 46, No. 1, pp. 206 – 212, Jan. 2000 for further details. The main advantage of generalizing the constraint is that for some sources the bounds may be tighter relative to EBB, and therefore more useful in providing improved network utilisation. Such traffic would,

however, not lead to a straight line bound in the Log P vs. Buffer plane (see Fig. 8) for all buffer sizes.

Considering the particular case where F has the form provided in Equation (13), the traffic, as noted, possesses EBB. In this case, the parameters which specify output from the ER are (ρ, α), rather than (ρ, σ) as in the TBR. In the ER context ρ now represents the mean output rate and α the probability slope parameter. By careful selection of the (ρ, α) parameter set, it can be shown that the output from the ER will always satisfy Equation (15), which is restated here for ease of reference :

$$\Pr\{O(t) - O(s) \geq \rho(t - s) + \sigma\} \leq e^{-\alpha\sigma} \quad (16)$$

for all s, $0 \leq s \leq t$.

Upon setting the value of α in the ER, the end user can specify a particular value for the upper bound on the probability of a given burst size σ being present in his traffic. This represents a practical method by which the user can make a service QoS specification to the network provider. The value of ρ must however be chosen so as to satisfy Equation (16). This requires that ρ be at least equal to the mean rate of the input traffic. Most traffic which can be described by a Markov process will be EBB as defined by Equation (16). See O. Yaron and M. Sidi, "Performance and Stability of Communication Networks via Robust Exponential Bounds", IEEE Transactions on Networking, Vol. 1, No. 3, pp. 372 – 385, June 1993 for more details.

Fig. 5 shows a block diagram representation of a preferred embodiment of the EBB/ER. Traffic is input on the input path 206 to the regulator 208, the traffic being input into a FIFO buffer 300. The contents of the buffer 300 are output onto the output path 102 under control of a buffer switch 400, the switch being controlled by an entropy regulation process 404 by means of a control signal depicted by a dashed line 402. The entropy regulation process 404 is notified of (i) the arrival of a packet in the buffer 300,

and (ii) the length 410 of the packet (denoted by L_i), by a signal 412 emanating from the buffer 300. The entropy regulation process 404 is characterised in terms of two input parameters, namely a probability slope parameter α input on a line 406, and a mean output rate parameter ρ input on a line 408. The entropy regulator 208 imposes an entropy bound on the incoming traffic on the path 206, thereby producing regulated output traffic on the path 102, the output traffic being characterised by a well defined entropy bound, EBB in the preferred embodiment. It is noted that the input traffic on the path 206 can be either traffic already having a well defined entropy bound, or alternatively, can be traffic whose characteristics are completely general. Accordingly, the entropy regulator 208 produces output traffic on the path 102 having a well defined entropy bound irrespective of the nature of the incoming traffic on the path 206.

Fig. 6 shows a preferred embodiment of an entropy regulation process 562, depicted by a flowchart of method steps relating to the entropy regulator described in relation to Fig. 5. Fig. 6 comprises a flowchart of method steps, in respect of which reference should be made to Table 1, and the subsequent explanatory notes.

i = packet number where subscript b mean packet is in buffer, initially i is zero and increments by one for every packet arrival.
L_i = packet length in bits For example L_{1_b} is the length of the first packet in the buffer
TOT is total number of bits to be transmitted
T_i^{IN} = Arrival time of packet at buffer
T_i^{OUT} = Departure time of packet from buffer
T_c = conforming time
t_C = current real time
$R = \frac{L_i + TOT}{T_i^{IN} - T_C}$
ρ = rate of Entropy Regulator
α = probability parameter of Regulator

Table 1

Explanatory Notes

W is calculated by selecting a random number x in the range 0-1 (uniformly) then setting

$$W(x) = F^{-1}(x)$$

For example the following function would result in EBB traffic

$$F^{-1}(x) = \frac{1}{\alpha}\log[1-x]^{-1}$$

The initial settings are T_c=0 and wait-time=0, clock=0

Turning to Fig. 6, the entropy regulation process 562 commences, in a step 560, by setting parameters α (ie. the probability parameter of the regulator), and ρ (ie. the rate of the entropy regulator).

For every packet arrival at the buffer 300 (see Fig. 5), this arrival being notified by the buffer 300 on the line 412 (see Fig. 5), the process 562 determines at what time the packet maybe output from the regulator 208. A packet arrival for a packet i is detected in a step 506, after which, a test in a step 507 is performed to determine if it is the first packet to arrive. If the packet i is the first packet (ie. i=1), then the process 562 is directed in accordance with a "yes" arrow to a set step 520, and then to an output step 535. If the packet i is not the first packet, then the process 562 is directed in accordance with a "no" arrow to a test step 508 where a test is performed for an "buffer empty" condition. If the buffer is found to be empty, then in accordance with an arrow 540, a variable R (see the explanatory notes for a definition thereof) is calculated, and then tested against ρ in a step 514. This is a conformance test which considers the length of the packet i, and that of a preceding packet, and also an arrival time for the packet i and a "conforming time" as shown in the notes in Fig. 6. If R is found, in the step 514, to be not greater than ρ, or equal thereto, then the regulator process 562 is directed in accordance with a "no" arrow 528 to the setting step 520, where the the conforming time and a number of bits (denoted

by *TOT*) which are able to be sent on the output line 102, are set as indicated. The process 562 then proceeds to the step 535 where the control signal 402 causes *TOT* bits of data from the regulator to be output on the line 102 (see Fig. 5). If, in contrast, *R* is found to be greater than or equal to ρ in the step 514, then the regulator process 562 is directed in accordance with a "yes" arrow 542 to a step 500, in which the packet *i* is left in the buffer 300.

Returning to the step 508, if the buffer 300 is found not to be empty, then the regulator process 562 is directed in accordance with a "no" arrow 552 to the step 500, where the packet *i* is left in the buffer. Following the step 500, the regulator process 562 is directed to a wait step 502, until a clock value exceeds a variable "wait-time", "and", the buffer 300 is not empty. Thereafter, in a step 504, the clock is reset and started again from zero, after which the regulator process 562 is directed, in accordance with an arrow 554, to a step 510 in which the value of the variable *W* is calculated. Thereafter, if the buffer occupancy according to a step 516 exceeds, or equals *W*, then the regulator process 562 is directed, in accordance with a "yes" arrow 530, to a determination step 522. If, on the other hand, in the step 516 the number of packets in the buffer is found to be less than *W*, then the regulator process 562 is directed to a setting step 518.

Returning to the determination step 522, this step determines the value of the parameter *n* as described. Thereafter, the regulator process 562 is directed to a testing step 524, where the value of *n* (determined in the step 522) is tested against zero. If *n* is not greater than zero , then the regulator process 562 is directed in accordance with a "no" arrow 536 to a step 526, where variables as described in the figure are set. Thereafter, the regulator process 562 is directed in accordance with an arrow 534, back to the waiting step 502.

Returning to the setting step 518, to which the regulator process 562 is directed in the event that the buffer 300 occupancy is less than W (see the step 516), variables are set, in the step 518 as indicated in the figure. Thereafter, the process 562 is directed in accordance with an arrow 546 to a step 513, in which the control signal 402 causes *TOT* bits of data from the regulator to be output on the line 102, after which the regulator process 562 is directed in accordance with an arrow 547 to a step 512 where a variable "wait-time" is set as indicated. Thereafter, the regulator process 562 is directed, in accordance with an arrow 548, back to the step 502. If the step 524 concluded that n was greater than zero, then the regulator process 562 is directed in accordance with a "yes" arrow 535 to a step 537 where variables as described in the figure are set. Thereafter, the regulator process 562 is directed to the step 513 where the control signal 402 causes *TOT* bits of data from the regulator to be output on the line 102. After this the regulator process 562 is directed in accordance with the path indicated by an arrow 547 as described above.

Two specific examples of entropy regulator settings are now described. In the first instance, an average bandwidth assignment example is described, wherein bandwidth is allocated to a user at the sustained rate ρ. This relates to the lower curve 708 in Fig. 4.

Traffic defined in this manner can be used in calculating buffer overflow probabilities. EBB traffic which enters a buffer with an output rate equal to the ρ of Equation (12) will have, as its bound, a straight line with slope α on the log P versus buffer occupancy graph (see Fig. 8). It is noted that this is not merely a straight line in the limit of large buffer occupancy (as is the case in large deviation theory). In fact, in terms of QoS, this case means that the end user knows precisely the bounded buffer occupancy spectrum.

This is a far more informative situation than that prevailing using token bucket regulators, which provide only a bound on maximum delay experienced by a packet. The

QoS can be characterized by the slope of the log P vs buffer occupancy graph. For a given buffer size in the network element, this graph will give the probability of data loss. Also the spectrum of delay of the data successfully carried can be determined. Knowledge of the bounded buffer occupancy spectrum can be used in various ways. If, for example, only a particular fraction of packets need to be transmitted through the network with a minimum delay, then less jitter can be imposed at the regulation stage on traffic relative to standard relative to standard regulation techniques.

Figs. 7 and 8 show an example of measured TCP data (described in V. Paxson and S. Floyd, "Wide Area Traffic: The Failure of Poisson Modelling", IEE/ACM Tran. On Networking, vol. 3 (3), pp. 226-244) before, and after regulation respectively, the traffic having been passed through a downstream buffer with leak rate ρ. It is noted that the data being considered in this example, possess long-range correlations, and cannot be modelled accurately using a Markov process. Figs. 7 and 8 illustrate the performance of the entropy regulator in producing a desired result. If, using standard bucket regulation, a small minimum delay was applied to all the packets, and a large part of the throughput spectrum would be rejected.

In a second example, bandwidth is allocated to a user on a "realistic control assignment" basis, where the bandwidth allocated to the user is greater than the sustained rate ρ. This example relates to the curve 706 in Fig. 4.

In this case, ρ is set equal to a mean of the probability density function g(x) associated with the distribution function F, which is expressed mathematically as follows:

$$\rho_m = \int_0^\infty xg(x)dx \qquad (17)$$

If ρ is now set to this value of ρ_m, the moment generating function $\Lambda(\theta)$ can be determined as follows:

$$\Lambda(\theta) = \log \int_0^\infty e^\theta g(x)dx, \tag{18}$$

and the effective bandwidth is then given by

$$\rho_e(\theta) = \frac{\Lambda(\theta)}{\theta} = \frac{\log}{\theta}\int_0^\infty e^\theta g(x)dx \tag{19}$$

If the entropy regulator is considered with a function F described by Equation (13), the effective bandwidth can be determined according to the following mathematical representation:

$$\rho_e(\theta) = \frac{\Lambda(\theta)}{\theta} = -\frac{1}{\theta}\log(1 - \frac{\theta}{\alpha}), \qquad (\theta < \alpha) \tag{20}$$

For another example, a Gaussian probability density function f(x) is assumed. In this case, effective bandwidth ρ_e is described as follows:

$$\rho_e(\theta) = \frac{\Lambda(\theta)}{\theta} = \rho_m + \frac{\theta\alpha^2}{2} \tag{21}$$

where in this case, α represents the standard deviation of the Gaussian distribution.

Considering the issue what amount of bandwidth the network management administrator can allocate to a new user who requests a QoS requirement , the relationship in Equation (19) can be used in order to calculate the effective bandwidth $\rho_e(\theta)$. This effective bandwidth can be checked against available bandwidth in the network, and allocated, or not, according to the available network store. This establishes a quantitative connection admission control procedure.

The imposition of the entropy regulator into the traffic stream results in traffic being forced to a zero rate output for some predetermined time. Accordingly, only approximation to an entropy function is established. This approximation is, however, accurate enough to provide real benefit in a real network environment.

A specific example highlights the use of the Entropy Regulator as follows. A user who has a 33 kbit/s link to a downstream network node which possesses a FIFO buffer B

bits with an output rate of 33 kbit/s is considered. If this user desires a QoS parameterized by a slope in the log P vs. buffer occupancy plot of this node equal to $2\text{x}10^{-4}$, the user sets the Entropy Regulator parameters to α=$2\text{x}10^{-4}$ and ρ=33k bit/s.

In this circumstance, regardless of the traffic that the user transmitted to the network, the conforming packets result in a bounded buffer occupancy characterized by a slope $2\text{x}10^{-4}$ in the log P vs. buffer occupancy plot. Indeed the plots of Fig. 7 (before regulation) and Fig. 8 (after regulation) show a simulation of this scenario. The curve 907 in Fig. 8 is indicative of a probability (ordinate) with which a particular buffer occupancy (abscissa) will be exceeded. It is desirable to operate at a low probability of overflow, since traffic is lost if a buffer overflows.

Alternatively if the downstream network node had a buffer size of B and the user requires a probability P that bits won't be discarded then he calculates α from the following mathematical equality:

$$\alpha = -\log(1-\mathrm{P})/B \qquad (22)$$

For example if the buffer size is 8000 bits and the user wants a no-loss probability of 99% an α of 5.7x 10^{-4} is selected.

If the network consists of a ER followed by a network element containing a buffer with output rate ρ_T, then the probability of the end-to-end delay spectrum d_j for the packet j can be determined. This is given by $(x \geq 0)$

$$P\{d_j \geq x\} \leq e^{-\alpha\rho x} \qquad (23)$$

Transmission and propagation delays experienced by the packet as it traverses the network have been ignored. An aggregation of N sources all with the same QoS requirements (*i.e.* same α) also have the same end-to-end delay spectrum, provided the downward link capacity ρ_T satisfied the following inequality:

$$\sum_{i=1}^{N} \rho_i \leq \rho_T . \tag{24}$$

More sophisticated uses can also be envisioned. In particular, if per-flow guaranteed-rate scheduling algorithms are deployed in the downstream nodes, the above equations can be used to determine the delay spectrum for multiple users who are all requesting different QoS specifications.

In order to explicitly appreciate an application of the Entropy Regulator to effective bandwidth theory for the example above, the ρ parameter of the Entropy Regulator is set to $\rho = 1/\alpha$. The Regulator then produces a probability density function for the output rate that is, to a close approximation, an exponential distribution with a sustained rate of 3 kbit/s. The effective bandwidth $\rho_e = \Lambda(\theta)/\theta$ is then determined to be approximately 4.6 kbit/s in order to obtain a QoS parameterized by $\theta = 10^{-4}$. This result also shows the capacity-reducing effects of the Entropy Regulator algorithm. In order to produce the required QoS result using pure effective bandwidth theory requires a reservation of bandwidth approximately 50% higher than that required to produce the same QoS result with the algorithm depicted in Fig. 6 (gain increases as θ approaches α).

This same effective bandwidth analysis can be used for any distribution function F in the algorithm depicted in Fig. 6. A function has been used which corresponds to the exponential distribution in the above discussion simply for illustrative purposes.

It is instructive to again highlight the advantages of using the Entropy Regulator instead of a TBR. The equation for the delay spectrum for entropy regulated flow can be compared with a similar equation for a flow passed through a Token Bucket Regulator with parameter ρ and σ;

$$d_j \leq \frac{\sigma}{\rho} \tag{25}$$

Again, transmission and propagation delays experienced by the packet as it traverses the network have been ignored. In this latter case it is clear that there is no information on the delay spectrum - only a deterministic worst case delay can be ascribed to the end-to-end delay of the packet. Furthermore, the output traffic from the TBR cannot, in general, be described by a Markov process, and as such a well defined entropy bound cannot be placed on it.

Accordingly, effective bandwidth theory cannot be applied to the output of a TBR in a quantitative fashion.

Another disadvantage of the TBR is that relative to the ER there can be additional jitter added to a flow when compared to the ER.

The method of entropy regulation of packet traffic can be practiced using a conventional general-purpose computer system 600, such as that shown in Fig. 9 wherein the process of Figs. 6 may be implemented as software, such as an application program executing within the computer system 600. In particular, the steps of method of entropy regulation of packet traffic are effected by instructions in the software that are carried out by the computer. The software may be divided into two separate parts, one part for carrying out the entropy regulation of packet traffic methods, and another part to manage the user interface between the latter and the user. The software may be stored in a computer readable medium, including the storage devices described below, for example. The software is loaded into the computer from the computer readable medium, and then executed by the computer. A computer readable medium having such software or computer program recorded on it is a computer program product. The use of the computer program product in the computer preferably effects an advantageous apparatus for entropy regulation of packet traffic in accordance with the embodiments of the invention.

The computer system 600 comprises a computer module 601, input devices such as a keyboard 602 and mouse 603, output devices including a printer 615 and a display device 614. A Modulator-Demodulator (Modem) transceiver device 616 is used by the computer module 601 for communicating to and from a communications network 620, for example connectable via a telephone line 621 or other functional medium. The modem 616 can be used to obtain access to the Internet, and other network systems, such as a Local Area Network (LAN) or a Wide Area Network (WAN).

The computer module 601 typically includes at least one processor unit 605, a memory unit 606, for example formed from semiconductor random access memory (RAM) and read only memory (ROM), input/output (I/O) interfaces including a video interface 607, and an I/O interface 613 for the keyboard 602 and mouse 603 and optionally a joystick (not illustrated), and an interface 608 for the modem 616. A storage device 609 is provided and typically includes a hard disk drive 610 and a floppy disk drive 611. A magnetic tape drive (not illustrated) may also be used. A CD-ROM drive 612 is typically provided as a non-volatile source of data. The components 605 to 613 of the computer module 601, typically communicate via an interconnected bus 604 and in a manner which results in a conventional mode of operation of the computer system 600 known to those in the relevant art. Examples of computers on which the embodiments can be practised include IBM-PC's and compatibles, Sun Sparcstations or alike computer systems evolved therefrom.

Typically, the application program of the embodiment is resident on the hard disk drive 610 and read and controlled in its execution by the processor 605. Intermediate storage of the program and any data fetched from the network 620 may be accomplished using the semiconductor memory 606, possibly in concert with the hard disk drive 610. In some instances, the application program may be supplied to the user encoded on a CD-

ROM or floppy disk and read via the corresponding drive 612 or 611, or alternatively may be read by the user from the network 620 via the modem device 616. Still further, the software can also be loaded into the computer system 600 from other computer readable medium including magnetic tape, a ROM or integrated circuit, a magneto-optical disk, a radio or infra-red transmission channel between the computer module 601 and another device, a computer readable card such as a PCMCIA card, and the Internet and Intranets including email transmissions and information recorded on websites and the like. The foregoing is merely exemplary of relevant computer readable mediums. Other computer readable mediums may be practiced without departing from the scope and spirit of the invention.

The method of entropy regulation of packet traffic may, alternatively, preferably be implemented in dedicated hardware such as one or more integrated circuits performing the functions or sub functions of entropy regulation of packet traffic. Such dedicated hardware may include graphic processors, digital signal processors, or one or more microprocessors and associated memories.

Industrial Applicability

It is apparent from the above that the embodiment of the invention is applicable to the telecommunications and computer network industries.

The foregoing describes only one embodiment of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiment being illustrative and not restrictive.

For example, the entropy regulator can be used in active programmable networks, where feedback mechanisms will allow end users to adjust entropy regulation parameters in realtime in order to achieve a desired quality of service. The network will,

in these cases, respond dynamically, using effective bandwidth processes to find, and allocate, the appropriate network resources.

The entropy regulator could also be used as a behavioural aggregate traffic conditioner at the edge of a Diffserv Domain. IETF documents RFC 2474, RFC 2475, RFC2597 and RFC 2598. Although the detailed use of the device in the Diffserv context would differ somewhat from the ATM - Call Admission Control set-up, the underlying principal use of it would be the same.

For use of illustration the regulator as described here has been used in conjunction with simple FIFO scheduling algorithms 209 (see Fig. 2). This type of scheduling can accommodate the QoS requirements of individual flows provided all flows have been regulated using the same QoS parameters. In the case where flows with differing QoS requirements are aggregated, the multiplexer, and other downstream network nodes, have to deploy more advanced scheduling algorithms , such as Weighted Fair Queuing. However, the use and operation of the Entropy Regulator remains the same as described.

The implementation of the regulator as described has been directed to operation in the shaping mode. Simple modifications to the algorithm depicted in Fig 6 however, allow the Regulator to be used in a policing mode. In this latter mode the Regulator does not buffer packets, but simply marks packets as being conforming or non-conforming. Downstream network elements are then left to decide how to deal with the non-conforming packets. Alternatively the Regulator can discard non-conforming packets. The use and operation of the Entropy Regulator remains the same, however, as described.

~~Claims:~~ The Claims defining the invention are as follows:

1. A method of regulating input packet traffic, said method comprising the steps of:

constraining said input packet traffic;

conforming said constrained input packet traffic in relation to a stochastic distribution function; and

producing output packet traffic having a well defined entropy bound.

2. A method according to claim 1; whereby said constraining step comprises a sub-step of:

inputting an amount of said input packet traffic into a buffer; and said conforming step comprises sub-steps of:

determining a buffer control signal dependent upon said stochastic distribution function and a content of said buffer; and

releasing at least part of said content as output traffic, dependent upon said buffer control signal.

3. A method according to claim 2; whereby

said stochastic distribution function is exponential; and

said well defined entropy bound is characterised by exponentially bounded burstiness.

4. A traffic regulator, comprising:

constraint means, adapted to constrain input traffic; and

conforming means adapted to conform said constrained input traffic to a stochastic distribution function to produce output packet traffic characterized by a well defined entropy bound.

5. A traffic regulator according to claim 4, wherein

said constraint means comprises a buffer responsive to a buffer control signal; and

said conforming means comprises a buffer control means adapted to determine said buffer control signal dependent upon at least one of said stochastic distribution function and a buffer content.

6. A method of regulating packet traffic, substantially as described herein with reference to the accompanying drawings.

7. A traffic regulator, substantially as described herein with reference to the accompanying drawings.

DATED this Twenty Seventh Day of April 2000

Commonwealth Scientific and Industrial Research Organisation

Patent Attorneys for the Applicant

SPRUSON & FERGUSON

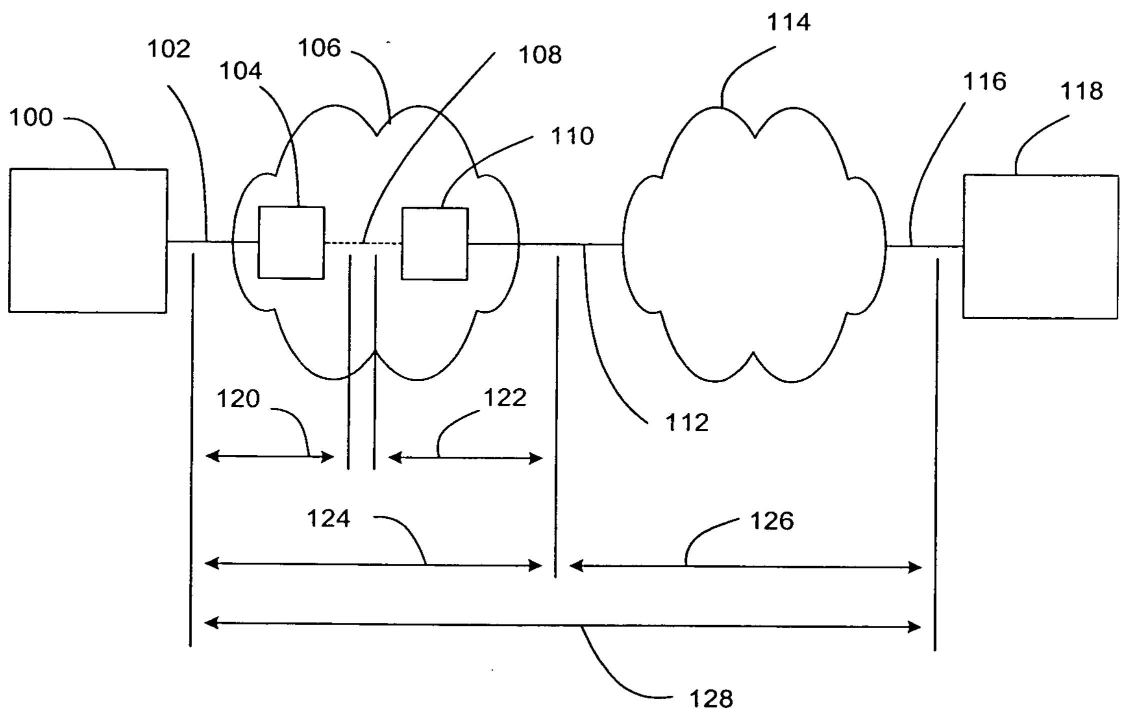


Fig. 1

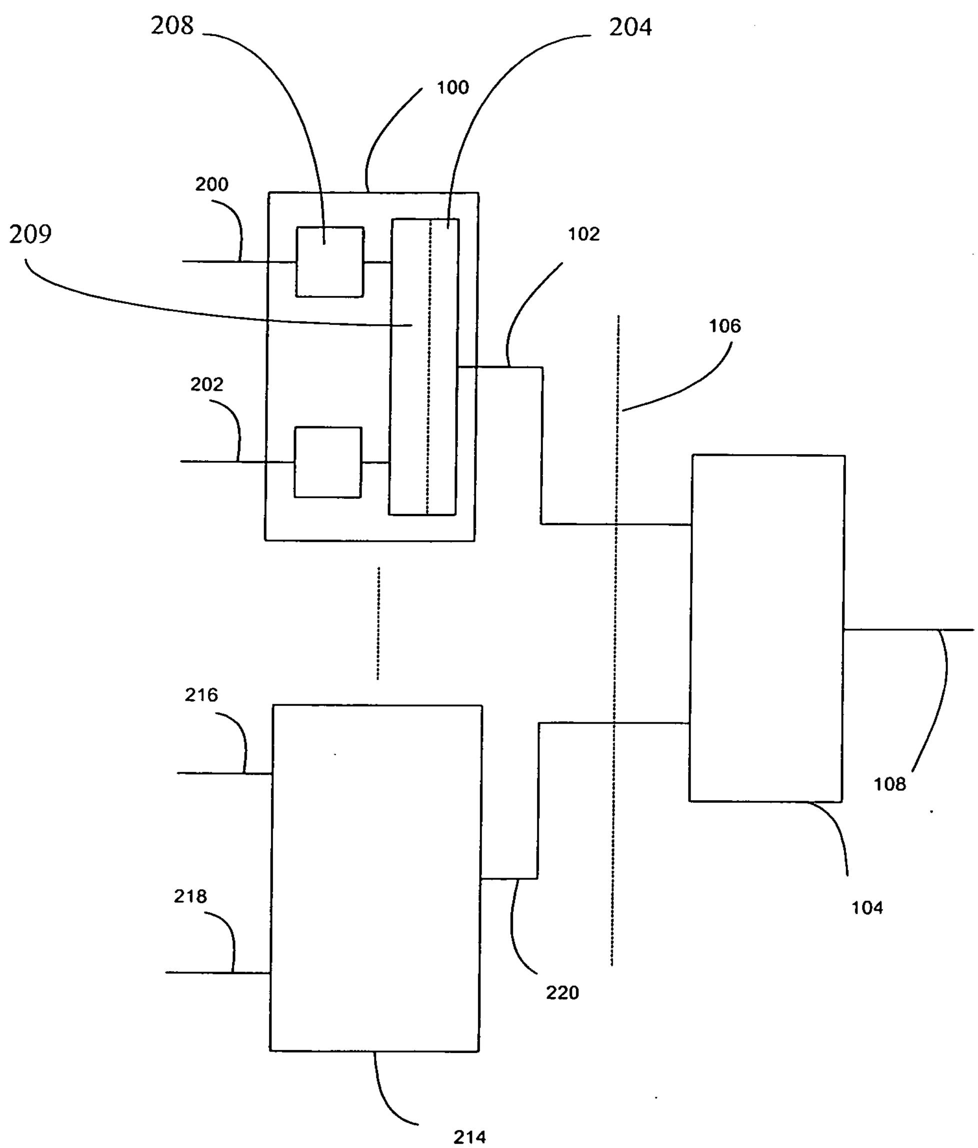


Fig. 2

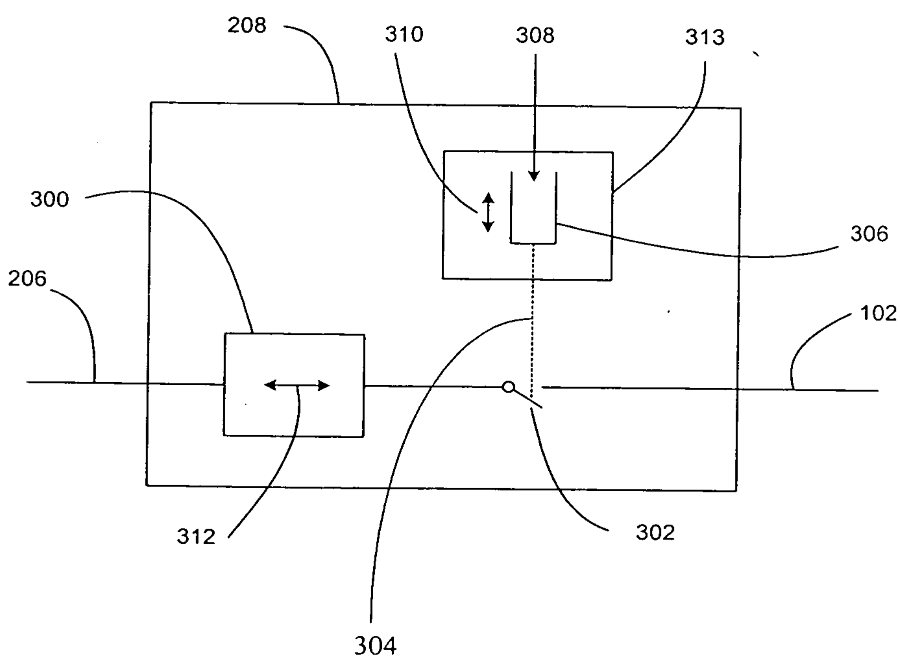


Fig. 3

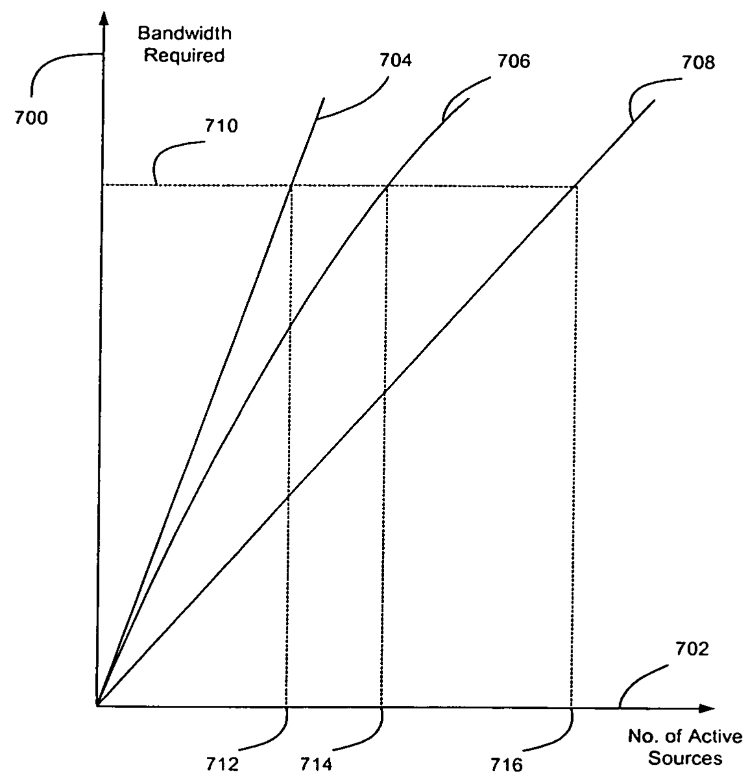

Bandwidth Required
700
704
706
708
710
702
No. of Active Sources
712
714
716

Fig. 4

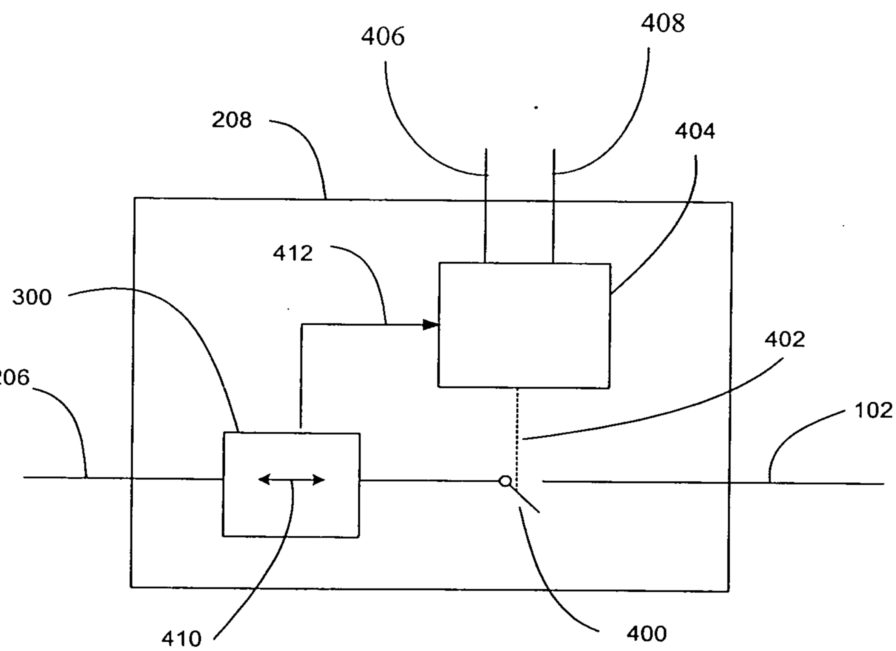
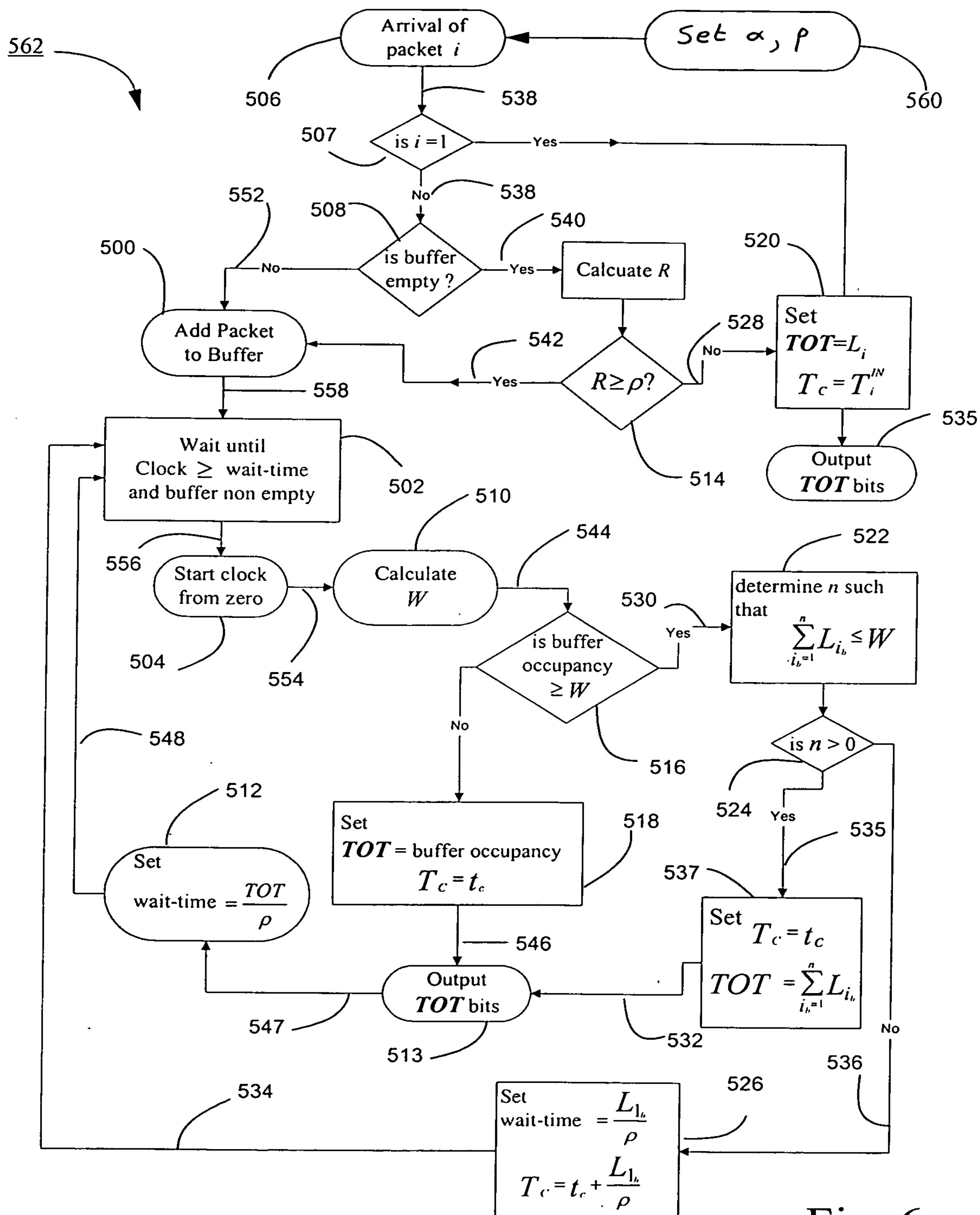


Fig. 5



562
Arrival of packet i
Set α, ρ
506
538
560
507
is i = 1
Yes
No
538
552
508
540
500
No
is buffer empty ?
Yes
Calcuate R
520
Add Packet to Buffer
542
528
Set TOT=L_i T_c = T_i^IN
Yes
R≥ρ?
No
558
535
Wait until Clock ≥ wait-time and buffer non empty
502
514
Output TOT bits
510
544
522
556
Start clock from zero
Calculate W
530
determine n such that Σ L_{i_b} ≤ W
Yes
is buffer occupancy ≥ W
504
554
No
548
516
is n > 0
512
524
Yes
518
535
Set TOT = buffer occupancy T_c = t_c
Set wait-time = TOT/ρ
537
Set T_c = t_c TOT = Σ L_{i_b}
546
Output TOT bits
547
532
513
No
536
534
526
Set wait-time = L_{1_b}/ρ T_c = t_c + L_{1_b}/ρ

Fig. 6

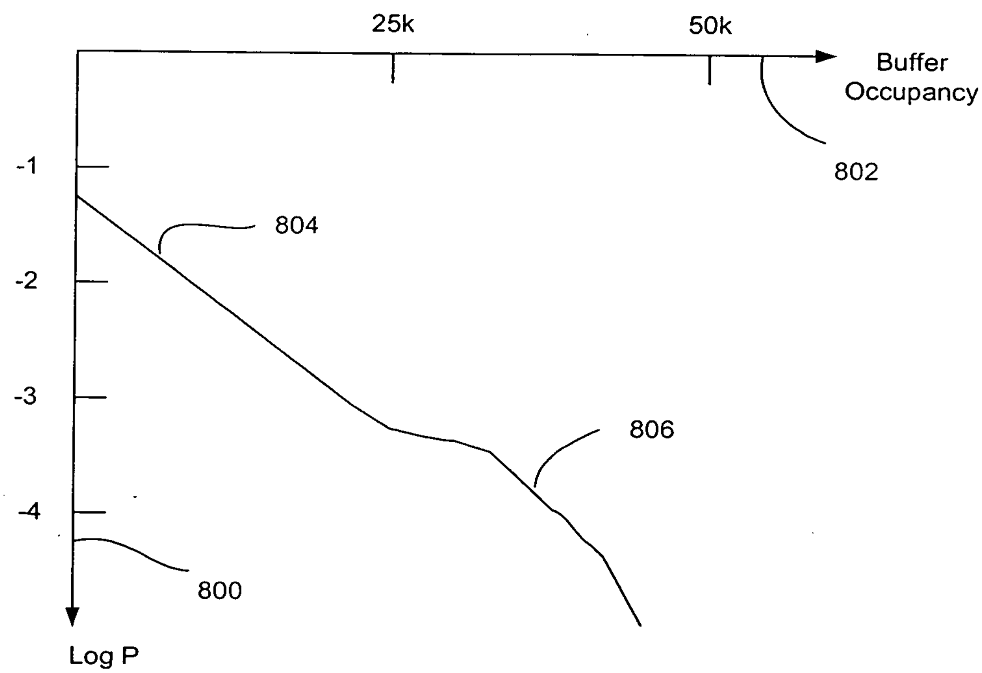


Fig. 7

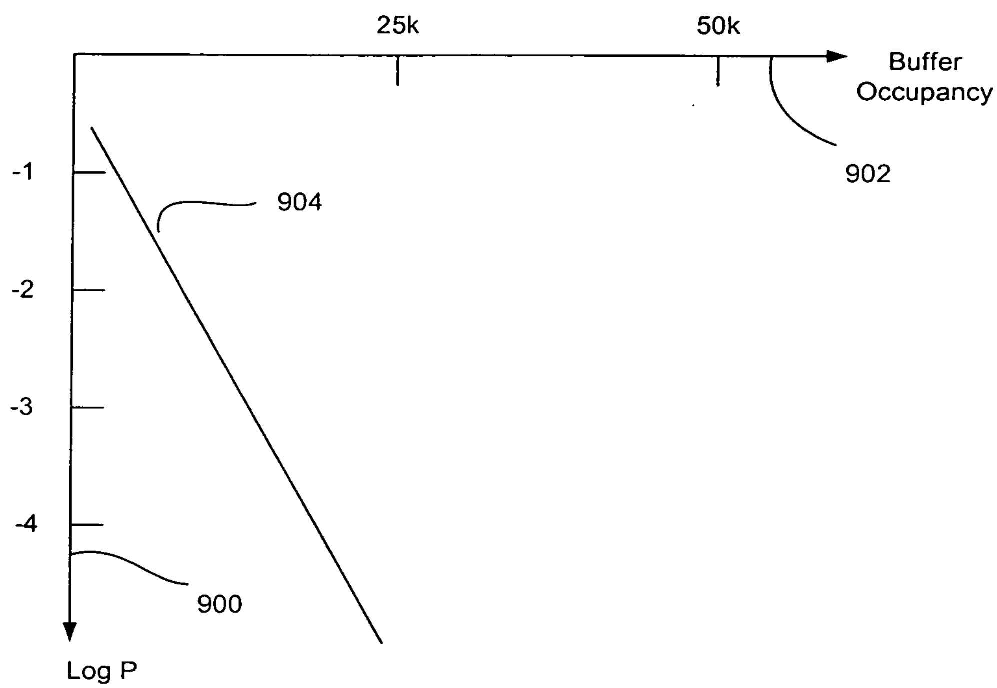
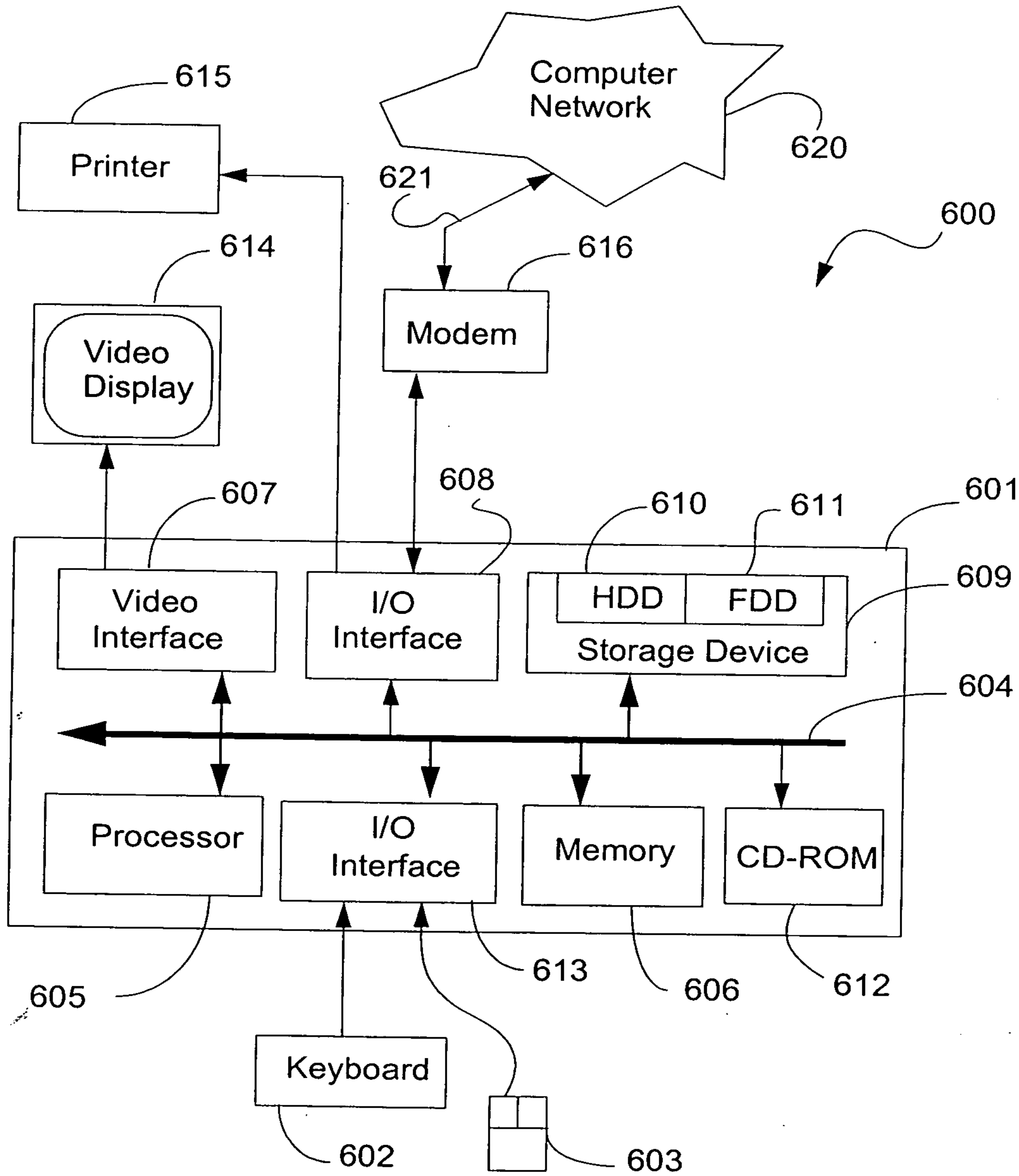


Fig. 8



Computer Network
620
615
Printer
621
600
614
616
Modem
Video Display
608
607
610
611
601
Video Interface
I/O Interface
HDD
FDD
609
Storage Device
604
Processor
I/O Interface
Memory
CD-ROM
613
606
612
605
Keyboard
602
603

Fig. 9